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Reduction of NO emissions in a turbojet combustor by direct water/steam injection: Numerical and experimental assessment

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ABSTRACT

Numerical and experimental investigations are conducted to assess the benefits and drawbacks of both water (mist) and steam direct injection within the combustion chamber of a 200 N static thrust turbojet. For this purpose, a three-dimensional CFD model of the combustion process is implemented where pollutant emissions are calculated; in parallel, a test campaign on the turbojet at sea level static conditions is carried out. In both cases the refrigerant flow is injected directly into the combustor, outside the liner. The aim of the investigations is to evaluate the impact of increasing water and steam flows (ranging from 0% to 200% of the fuel mass flow) onto the emissions levels (NO and CO) of the engine.

1. Introduction and background

Pollutant emissions arising from oxidation processes in aeronautical combustion chambers have recently become of great concern due to their environmental impact. Emissions of nitrogen oxides from aircrafts, which affect men's health and contribute to the formation of ozone, have been of particular interest to many airport operators as a result of increasing air traffic.

Since the end of World War II water injection in aero-engines has been quite extensively studied [1–3], and was implemented mainly for thrust augmentation [4] even at supersonic flight conditions [5,6]. Such "old-style" water injection systems used on early Boeing 707 and 747 aircraft were unpopular with airlines because little benefit was readily seen while the drawbacks of servicing the system with water were observed every day. Since those times, interest regarding water injection in aero-engines has dropped down until the beginning of the new century.

Recently, the use of water injection has been again proposed as an effective tool to reduce emission levels, particularly NO_x, during taxiing and take-off operations [7–13]. The most comprehensive study was carried out at NASA Glenn Research Center to estimate the effects of water injection on a commercial turbofan engine to reduce specific fuel consumption (SFC), NO_x emissions, and engine hot-section temperatures while maintaining constant thrust [7]. According to these results, the subsequent reduction in hot-section temperatures could increase engine life and reduce maintenance costs. Water injection technique is very similar to the one employed in industrial gas turbine combustors, where water injection is currently used for power augmentation, turbine life saving and NO_x reduction during the hot seasons [13,14]. It consists basically in injecting finely atomized (misted) water into the engine's low pressure compressor or directly in the combustion chamber [15]. Water misting evaporates purified water to reduce the temperature of the engine inlet air and makes for a denser mixture. As opposed to old style water injection schemes, this approach has additional potential benefits of reduced Specific Fuel Consumption (SFC) and emissions, as well as greatly reduced turbine inlet temperature.

In an aircraft engine, the water can be conveniently carried on board in an appropriate tank and delivered only during the taxiing and take-off without paying too much in terms of extra weight for the overall aircraft. This is a consequence of the relative small mass necessary, which are of the same order of magnitude of the fuel needed during take-off. In the case of steam, some of the heat produced by the engine combustion could be employed in specific heat exchangers to generate the required amount of steam. As a matter of fact, almost all the engines could take advantage from this technique, from small to high by-pass turbofans and open rotor engines.

On the other hand, based on some experiments conducted in the past [16], Benini and Mistè have recently modeled the effect of steam injection directly within an aeronautical combustor in order to study its effect on both the liner cooling and combustion efficiency [17]. They also observed a significant shift toward lower values in the temperature distribution within the combustor, a phenomenon which could be conveniently exploited to reduce the thermal NO_x. More recently, Molnar and Marek [18] developed a mathematical model for the simulation of Jet-A and methane fuels including water injection to be used in numerical combustion codes, and ended up in a correlation that gives the chemical kinetic time of the fuels investigated. Although the main scope of their

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Nomenclature

A	Eddy dissipation model constant
B	Eddy dissipation model constant
Da	Damköhler number
g	acceleration of gravity = 9.8066 m/s^2
h	specific enthalpy
I, $[I]$	generic species, molar concentration of species I
$\bar{J}^z$	diffusive flux of chemical species z
k	turbulent kinetic energy per unit mass
N_c	number of chemical species
p	static pressure
Pr	laminar Prandtl number, Pr = $c\mu/\lambda$
Pr$_t$	turbulent Prandtl number, Pr$_t$ = $c\mu_t/\lambda t$
$\vec{q}$	heat diffusive flux
$\dot{Q}_{rad}$	radiative heat flux
R	universal gas constant
R_z	elementary reaction rate of progress for reaction z
Sc	Schmidt number
t	time
$\vec{u}$	velocity vector $\vec{u}{=}_1 + u_2 + u_3$
$\dot{w}_I$	mass reaction velocity of chemical species I
$\vec{x}$	position vector
Y_z	mass fractions of chemical species z
Greek symbols	
δ_{ij}	identity matrix or Kronecker delta function
ε	turbulence dissipation rate
λ	thermal conductivity
λ_t	turbulent thermal diffusion coefficient
μ	molecular (dynamic) viscosity
μ_t	turbulent viscosity
ρ	density
τ	viscous stress tensor
ϕ	generic quantity
$\tilde{\phi}$	Favre-average of generic quantity
ϕ''	random fluctuation of generic variable
v_{zI}	stoichiometric coefficient for component I in the elementary reaction z

work was to develop a numerical tool to better describe the kinetics of the burned fuels, they demonstrated how significant is the water injection in modifying the nature of the chemical reaction involved in the combustion and in reducing NO_x formation. Other relevant results on modelling combustion including water injection are given in [19–21].

In this paper, numerical and experimental studies are conducted to assess the potentialities of both water and steam injection in a small turbojet combustion chamber as far as NO reduction and cooling effect are concerned.

2. Mathematical model

A numerical model is applied to solve for the thermo-fluid dynamic flow field inside a generic combustor, where compressible and reactive phenomena, including heat transfer, occur. For this purpose, the ANSYS CFX© package is used. Equations implemented in the software are the following:

Conservation of mass (continuity):

$$\frac{\partial \rho}{\partial t} + \frac{\partial(\rho u_i)}{\partial x_i} = 0 \quad i = 1,2,3 \tag{1.1}$$

Transport of chemical species:

$$\frac{\partial(\rho Y_z)}{\partial t} + \frac{\partial(\rho Y_z u_i)}{\partial x_i} = -\frac{\partial J_i^z}{\partial x_i} + \dot{w}_z \quad z = 1,2,\ldots,N_c \tag{1.2}$$

Conservation of momentum:

$$\frac{\partial(\rho u_j)}{\partial t} + \frac{\partial(\rho u_j u_i)}{\partial x_i} = -\frac{\partial p}{\partial x_j} + \frac{\partial \tau_{ij}}{\partial x_i} + \rho g_j \tag{1.3}$$

Conservation of specific enthalpy:

$$\frac{\partial(\rho h)}{\partial t} + \frac{\partial(\rho h u_i)}{\partial x_i} = -\frac{\partial q_i}{\partial x_i} + \frac{Dp}{Dt} + \tau_{ij}\frac{\partial u_i}{\partial x_i} + \dot{Q}_{rad} \tag{1.4}$$

The partial pressure of each species is calculated using Dalton's law for ideal gases:

$$p = \sum_z p_z \Rightarrow p_z = pY_z = \rho RTY_z \tag{1.5}$$

while the viscous stress tensor is expressed using Newton's equation:

$$\tau_{ij} = \mu\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right) - \frac{2}{3}\mu\delta_{ij}\left(\frac{\partial u_i}{\partial x_i}\right) \tag{1.6}$$

and the diffusive flux of chemical species z is expressed by the Fick's law:

$$\bar{J}^z = -\frac{\mu}{\mathrm{Sc}_k}\frac{\partial Y_z}{\partial x_i} \tag{1.7}$$

where Sc is the Schmidt number.

The generic source term q_i is modeled as:

$$q_i = -\frac{\mu}{\mathrm{Pr}}\left[\frac{\partial h}{\partial x_i} + \sum_{z=1}^{N_c}\left(\frac{\mathrm{Pr}}{Sc_z} - 1\right)h_z\frac{\partial Y_z}{\partial x_i}\right] \tag{1.8}$$

being Pr the Prandtl Number.

To solve for the turbulent flow, the Favre Averaged Navier–Stokes (FANS) assumption has been considered [22]. This is particularly suitable for reacting flows, where high density variations take place. In this approach, the general quantity is split into two components: its time-density- averaged value over a period of time T' and a component that fluctuates with time:

$$\phi = \frac{\int_{T'}\rho(t)\phi(t)dt}{\int_{T'}\rho(t)dt} + \phi'' = \frac{\widetilde{(\rho\phi)}}{\tilde{\rho}} + \phi'' = \tilde{\phi} + \phi'' \tag{1.9}$$

Rewriting the equations of conservation, we obtain:

$$\begin{aligned}
&\frac{\partial\tilde{\rho}}{\partial t} + \frac{\partial\tilde{\rho}\langle u_i\rangle}{\partial x_i} = 0\\
&\frac{\partial\tilde{\rho}\langle Y_z\rangle}{\partial t} + \frac{\partial\tilde{\rho}\langle Y_z\rangle\langle u_i\rangle}{\partial x_i} = -\frac{\partial\tilde{\rho}\langle Y_z'' u_i''\rangle}{\partial x_i} - \frac{\partial\widetilde{J_i^z}}{\partial x_i} + \widetilde{\dot{w}_z}\\
&\frac{\partial\tilde{\rho}\langle u_j\rangle}{\partial t} + \frac{\partial\tilde{\rho}\langle u_j\rangle\langle u_i\rangle}{\partial x_i} = \frac{\partial\tilde{\rho}\langle u_j'' u_i''\rangle}{\partial x_i} - \frac{\partial p}{\partial x_j} + \frac{\partial\tilde{\tau}_{ij}}{\partial x_i} + \tilde{\rho}g_j\\
&\frac{\partial\tilde{\rho}\langle h\rangle}{\partial t} + \frac{\partial\tilde{\rho}\langle h\rangle\langle u_i\rangle}{\partial x_i} = -\frac{\partial\tilde{\rho}\langle h'' u_i''\rangle}{\partial x_i} + \frac{D\tilde{p}}{Dt} - \frac{\partial\widetilde{J_i^z}}{\partial x_i} + \tau_{ij}\frac{\partial u_j}{\partial x_i} + \tilde{\dot{Q}}_{rad}
\end{aligned} \tag{1.10}$$

The viscous Reynolds stresses are modeled using the standard k–ε model [23].

The turbulent mass and heat fluxes are modeled using the gradient transport hypothesis:

$$\tilde{\rho}\langle Y_z'' u_i''\rangle = -\frac{\mu_t}{\mathrm{Sc}_{zt}}\frac{\partial\langle Y_z\rangle}{\partial x_i}$$
$$\tilde{\rho}\langle h'' u_i''\rangle = -\frac{\mu_t}{\mathrm{Pr}_{zt}}\frac{\partial\tilde{\rho}\langle h\rangle}{\partial x_i} \quad (1.11)$$

The rate of production/consumption for the generic species has to be expressed by a combustion model, being a highly non linear function of temperature. In a generic combustion reaction that can be described in terms of z elementary reactions involving N_c components $\sum_{I=1}^{N_c} v'_{zj} I \Longleftrightarrow \sum_{I=1}^{N_c} v''_{zj} I$, where v_{zj} is the stoichiometric coefficient for species I in the elementary reaction z, the rate of production/consumption for I can be computed as the sum of the rate of progress for all the elementary reactions in which component I participates $\dot{w}_I = W_I \sum_{z=1}^{K}(v''_{zI} - v'_{zI})R_z$, being R_z the elementary reaction rate of progress for reaction z, which can be calculated using the Eddy Dissipation model [24], which is fully integrated in the software package, that was developed for a wide range of turbulent reacting flows. Such model is based on the assumption that chemical reactions are fast relative to the transport processes in the flow; it is valid for high values of Reynolds and Damköhler numbers, the latter relating the mixing efficiency of the reactants and their kinetic reaction $\mathrm{Da} = \frac{\tau_{turb}}{\tau_{chem}}$.

When reactants mix at the molecular level, they instantaneously form products and the rate of combustion is determined by the rate of intermixing on a molecular scale of fuel and oxygen eddies. The model assumes that the reaction rate may be related directly to the time required to mix reactants at the molecular level. In turbulent flows, this mixing time is dominated by the eddy properties and, therefore, the rate is proportional to a mixing time defined by the turbulent kinetic energy, k, and turbulent dissipation rate ε. In particular, the rate of progress of elementary reaction z is determined by the minimum of the following expression:

$$R_z = A\frac{\varepsilon}{k}\min\left[\min\left(\frac{[I]}{v'_{zI}}\right), B\min\left(\frac{\sum_P W_I[I]}{\sum_P W_I v''_{zI}}\right)\right] \quad (1.12)$$

where $[I]$ is the molar concentration of species I and includes only the reactant components; A and B are two constants of the model. Previous equation is assumed to be applicable to diffusion as well as to premixed flames; the term that gives the lowest value is the one that determines the local rate of combustion. Assuming that the problem is the one in which a stable flame must be established, to start and maintain a stable flame an initial specification of product within the calculation domain is sufficient.

In order to model the radiation intensity source term $\dot{Q}_{rad}$, a $P-1$ model (also known as the Gibb's model or Spherical Harmonics model) is chosen [25] which assumes that the radiation intensity is isotropic or direction-independent at a given location in space.

2.1. NO formation model

The NO formation model is fully integrated into the software's reaction and combustion module and accounts for the following NO formation mechanisms: thermal NO, prompt NO, Fuel Nitrogen, N_2O and reburn (destruction of NO) [26].

3. Case study

The numerical model outlined above was implemented and applied to study the behavior of a small direct-flow annular-type combustor mounted in a research turbojet engine developed at the University of Padova and described in [27], see Fig. 1. The reader is referred to [27] for a complete and detailed description of both the engine and the combustion chamber.

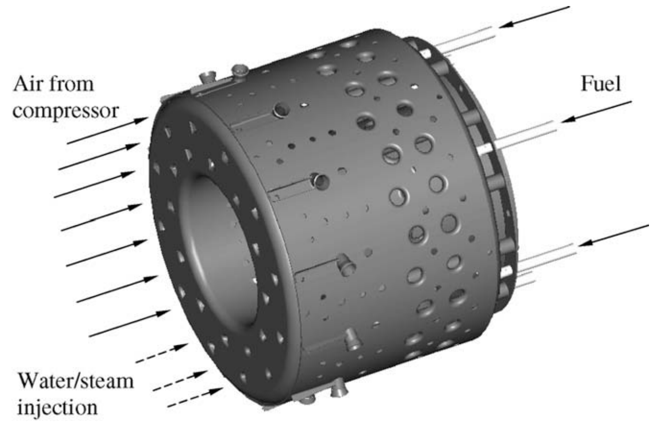

Fig. 1. Computer representation of the combustion chamber.

In order to analyze the influence of water and/or steam injection, a supplementary pump is used which conveys the above fluids directly in the chamber by using copper pipes. These are insulated when the effect of water injection is investigated and insulation-free when the steam is to be produced. In the latter case, a part of the heat developed during the combustion is used to evaporate the water. To reach an efficient combustion and to exploit an effective refrigerating effect, the steam/water injection point is put far away from the reaction zone and near the chamber walls. If a direct interaction with the reagents was achieved, the oxidation reaction could fail; in fact, in the best case the combustion would be incomplete featuring a lot of by-product and unburned fuel emissions, or, at worst, no reaction would take place. In this study, the refrigerant inlet is positioned under the air main inlet region to satisfy these needs (i.e. much closer to the engine axis of rotation). Fig. 2 better clarifies the location of the refrigerant inlet. As a matter of fact, this was the position for which the most effective NO reduction was achieved without paying too much in terms of both flame stability and combustion efficiency.

At nominal conditions, the engine is fed using Jet A, a kerosene grade of fuel suitable for most turbines civil aircraft having has a flash point above 38 °C and a freeze point maximum of −47 °C. Jet A meets the requirements of British specification DEF STAN 91–91 (Jet A-1), (formerly DERD 2494 (AVTUR)), ASTM specification D1655 (Jet A-1) and IATA Guidance Material (Kerosene Type), NATO Code F-35.

The engine combustor is operated as follows: at engine start-up, electric power from the auxiliary motor is used to accelerate the core-assay to approximately 10,000 rpm. At this point the ignition is turned on, and a natural-gas-fuel is used to light up the combustion process. Next, further acceleration of the engine to its mini-

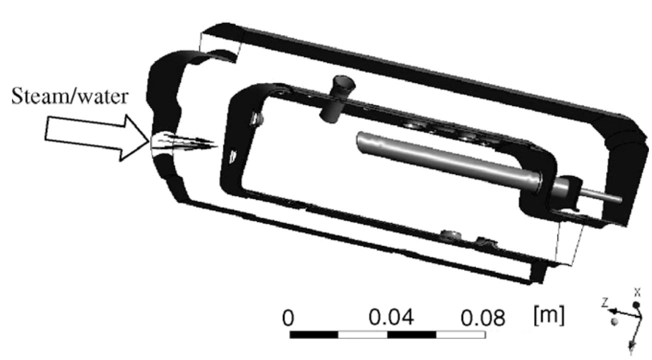

Fig. 2. Refrigerant inlet region.

mum idle speed of approximately 20,000 rpm occurs. From this point, the electric motor is disconnected and the engine is self-operated. The thrust then produced can be quite easily controlled by acting on the fuel flow rate, which in turn determine the instantaneous rotational velocity of the turbojet. A changeover from natural-gas to Jet A is accomplished using the same fuel manifold system, by simultaneously closing the gas-fuel valve and opening the liquid-fuel valve. During changeover, the turbojet engine runs on a mixture of gas-fuel and Jet A for a few seconds. Further acceleration to the engine's maximum continuous speed of 60,000 rpm can then be initiated. When the engine operation is stable, the water/steam injection can eventually be started and its effects analyzed.

4. Numerical simulations and experimental campaign

Due to the axial symmetry of the combustor, only a 30° sector was simulated in the numerical model, as represented in Fig. 2, where a tetrahedral mesh is created inside the flow domain. The grid features a minimum edge length of 0.123 mm and a maximum of 3 mm, about 240,000 nodes and 1,252,000 elements.

Table 1 shows the boundary conditions applied to the domain inlet and outlet stations, as well as the fuel properties.

As far as the water/steam injection are concerned, two types of simulations are conducted: in the former, the effects of steam injection are evaluated by considering three steam flows equivalent to 0%, 100% and 200% of Jet A flow; in the latter, water injection (at 25 °C) is investigated for the same mass flow ratio relative to Jet A and a comparison between steam and water injection is conducted.

The same operating points of the combustor, including water/steam injection, were analyzed experimentally. The turbine inlet temperature was measured, along with pollutant emissions (CO and NO).

5. Results and discussion

The results obtained after the simulations and the experimental assessment show how the principal emissions of the combustor can be reduced with the introduction of steam or demineralized water in the combustion chamber.

Fig. 3 shows the effect of the refrigerant on the turbine inlet temperature as a result of both the calculation and the experimental acquisitions. Outlet temperature from the combustion chamber presents in fact almost a linear decrease with the refrigerant flow. From this point of view, an augmented cooling effect is registered with water injection, as expected.

The most important consequence of this effect is the related decrease in thermal NO emissions and, when steam is used, the

Table 1
Boundary conditions of the simulations (30° sector).

Air inlet	Air flow (kg/s)	0.044
	Total temperature (K)	407
Fuel inlet	Fuel flow (kg/s)	$3.69 * 10^{-4}$
	Total temperature (K)	300
	Fuel properties	Type JET A
		Ignition point (fire point) 38 °C
		Auto-ignition point 210 °C
		Freezing point −40 °C
		Maximum fire point 980 °C
Combustor	Heat transfer	Active, conductive walls, outer walls adiabatic
	Thermal radiation	Opaque
Outlet	Relative pressure (Pa)	246,000
Periodic walls	For any options	Conservative interface flux

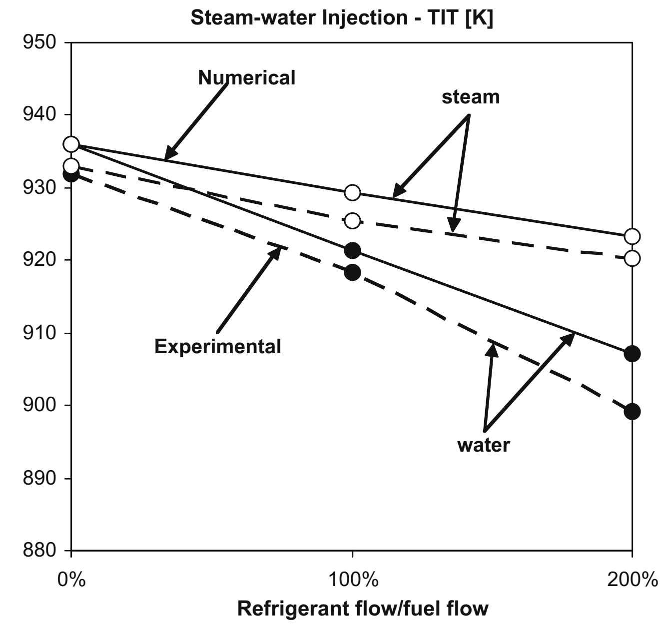

Fig. 3. Comparison between computed (solid lines) and experimental (dashed lines) TIT temperature values using steam and water injections.

appearance of a minimum in the amount of CO. Fig. 4 displays a comparison between computed and measured emissions using steam injection. Fig. 5 shows the same dependence obtained using water.

From Fig. 4, a NO reduction of about 16% can be appreciated when the steam flow doubles the fuel flow. On the other hand, the temperature drop triggers the rise of CO and unburned fuel due to incomplete oxidation. However, this phenomenon is registered only at relatively high values of the steam flow: in fact, when the steam flow equals the fuel flow a small decrease in the CO emission is found both numerically and experimentally. This can be explained by the fact that, at relatively small quantities, steam promotes turbulent mixing of fuel and air, thus resulting in zones where the mixture strength is enhanced with respect to the baseline case (where no steam is injected).

As far as the water injection is concerned, the following considerations can be drawn. A less effective NO reduction, compared to

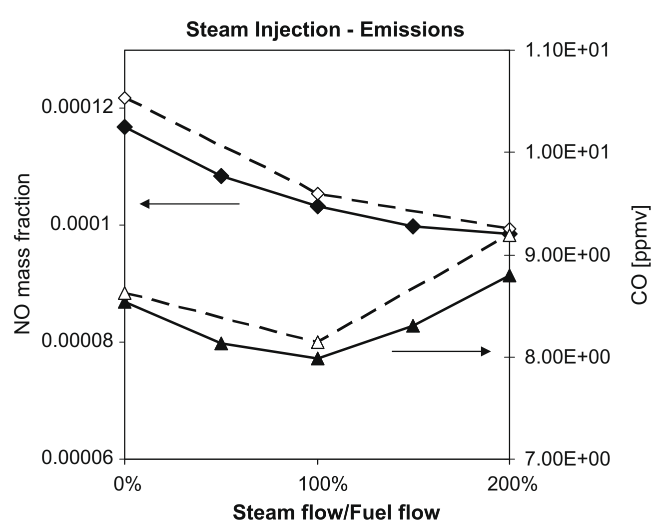

Fig. 4. Comparison between computed (solid lines) and measured (dashed lines) emissions using steam injection.

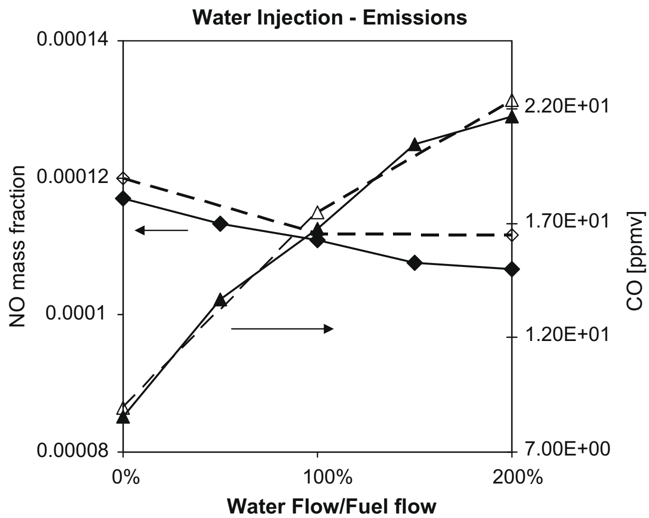

Fig. 5. Comparison between computed (solid lines) and measured (dashed lines) emissions using water injection.

steam injection, is registered both numerically and experimentally (Fig. 5). Moreover, a substantial increase in the CO production can be appreciated. This is due to the inadequate burning rated in the primary zone of the combustion chamber, where the water tends to withstand fuel/air mixing. As a consequence, steam injection is preferred to water injection when a reduction in the NO emissions is to be pursued while maintaining relatively low CO emissions.

6. Conclusions

Experimental and numerical analyses show that, in this particular turbojet, steam and water injections permit a reduction in NO emission and confirm their effectiveness as refrigerants of the combustion gases. From this point of view, steam injection reduces the NO emissions up to 16% (in terms of mass fraction) when a steam flow which doubles the fuel flow is introduced, whereas a reduction of about 8% is found using water injection in the same proportions to fuel flow. On the other hand, a much higher cooling effect on outlet combustion gases is produced by water instead of steam (due to the much higher thermal capacity of water). However, a significant difference in the amount of CO produced is registered. While the CO levels reduces slightly with steam injection, their value tends to increase more and more as higher quantities of water are injected.

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